PAC33 Proposal

“In-medium Properties of the ρ, ω, and ϕ Mesons”

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Abstract

We propose a new experiment with a photon beam up to 3 GeV on a set of nuclear targets (^{2}H, C, Fe, Nb, and Sn) using the CLAS detector. The experiment is designed to study the in-medium properties of the light vector mesons via their rare leptonic decay. This decay channel is preferred over the hadronic modes in order to eliminate final state interactions in the nuclear matter. The in-medium modifications is a broad field encompassing quark effects such as partial restoration of chiral symmetry and nuclear many-body effects such as modified coupling constants and the opening of new decay channels. Recent predictions have indicated that there is a momentum dependence of the in-medium properties.

In the previous experiment (g7a experiment), the primary goal was to study the ρ meson which is clearly seen in all the targets. The published result has clearly demonstrated the ability of the CLAS detector to detect the e^+e^- decay of all three vector mesons, and to extract, free of background, the experimental mass distribution of the ρ meson. These results have ruled out large medium effects, $\alpha \geq 0.053$, with a 95% confidence level, as predicted by Hatsuda and Lee (QCD sum rule, $\alpha = 0.16 \pm 0.06$), and Brown-Rho scaling. The proposed experiment will expand the investigation of in-medium properties of the ρ, ω, and ϕ mesons. It will have a strong impact on the field by mapping out the momentum dependence of the in-medium properties. The proposed measurement with CLAS will produce clean ρ mass spectra in four momentum bins from 0.5 GeV to 2.5 GeV with the same sensitivity as the previous measurement. Directly measuring the absorption of the ω and ϕ mesons in nuclei will provide information about the broadening of the in-medium widths. The increase in statistics will be obtained by increasing the instantaneous luminosity ($\times 2.5$) and the running time to 36 days ($\times 2$) over the previous measurement. The unique characteristics of the medium-modification program with CLAS are an electromagnetic probe and a final state uncomplicated by strong interactions that provides a direct measurement of the vector meson properties in the medium.

1 Preface

The previous experiment has made its impact on the field of medium modifications. It has produced a successful result for Hall B and Jefferson Lab. At numerous international conferences, it has been recognized for its high quality and rigorous limit on possible modifications to the properties of the ρ meson. The results have been published in Physical Review Letters [1]. Presently, an article for Physical Review C is in CLAS collaboration review. This result rules out the prediction of Brown and Rho [2] for a mass shift of the ρ on the order of 20% and a mass shift parameter $\alpha = 0.16 \pm 0.06$ for the ρ meson in carbon and iron targets as calculated by Hatsuda and Lee [3]. The mass shift parameterization α will be discussed in Section 2.2. Due to this result in part, the theoretical models have evolved to consider new aspects of medium effects such as momentum dependence and what happens to the ω and ϕ mesons.

In light of our impact, the new proposal has refocused the study of in-medium properties of the vector mesons in the following manner:

- Investigate the momentum dependence of the in-medium properties of the ρ meson in Fe and Nb nuclei which is of great interest to the theoretical community. The proposed experiment will be the first to measure the momentum dependence on the in-medium properties. The data with the Nb target will provide another data point at a higher effective density.

- Study in-medium broadening of the ω and ϕ mesons by measuring the absorption of the vector mesons in nuclei. The momentum dependence of the ω- and ϕ-meson widths will be studied for greater understanding of the broadening effect.

A major benefit of the new experiment will be an even tighter constraint on the ρ meson measurement when the data is analyzed over the entire momentum range. At JLab, all three mesons will be detected in the same experiment as opposed to the TAPS experiment which only measured the ω meson and the SPRING8 experiment which only measured the ϕ meson. With the CLAS detector, the mass spectra will have low-background and clearly-defined meson signals over a wide range of momentum.

This document is an updated and significantly-modified version of proposal PR-06-102 submitted to PAC 30. The PAC 30 report is discussed here, and the comments are addressed.

1.1 PAC 30 Comments

The PAC 30 report on PR-06-102 is reproduced as follows:

Proposal: PR-06-102

Scientific Rating: N/A

Title: Search for the Modification of Vector Meson Properties in Nuclei

Spokespersons: D. P. Weygand, C. Djalali, R. Nasseripour, and M. H. Wood

Motivation: Experiments of this type are aimed at a very important issue in nuclear physics. There has been a world-wide effort to determine the existence of medium modifications in nuclei and experiments of this type represent an outstanding opportunity for JLab. The idea of photoproducing the ρ is excellent since the photons should illuminate the entire nucleus more uniformly than hadron induced production. The idea to detect lepton pairs from ρ decay is also excellent for the same reason.

Measurement and Feasibility: The measurement relies on extracting the ρ resonance from relatively large background conditions. The collaboration has made an enormous effort at understanding the background in the g7a experiment and it appears that the ρ peak can be reasonably isolated and its parameters measured for D, C and Fe nuclei. The g7a data appear to have placed a very tight constraint on medium modifications, yielding a value for the alpha parameter in the Hatsuda-Lee formulation of 0.02 +- 0.02. This contradicts several other experiments which found large medium modification effects for the vector mesons in nuclei.

Issue 1: The Nb target provides a limited lever arm beyond the Fe results and a large increase in the background conditions.

Response: The Nb target is the optimal choice for a heavier nucleus. Fig. 1 shows the calculated average effective density with respect to A. From deuterium to carbon, there is a large increase in effective density. After carbon, the effective density increases much slower to a value for Fe at approximately 0.50. For Nb, the effective density increases to about 0.55, and with Pb, the effective density reaches a value of 0.58. With the cross section for electromagnetic background increasing as a function of Z^2, a Pb target will produce 4 times the background as Nb with a 3% gain in average effective density. A Nb target will provide the higher average effective density without overwhelming the data with background.

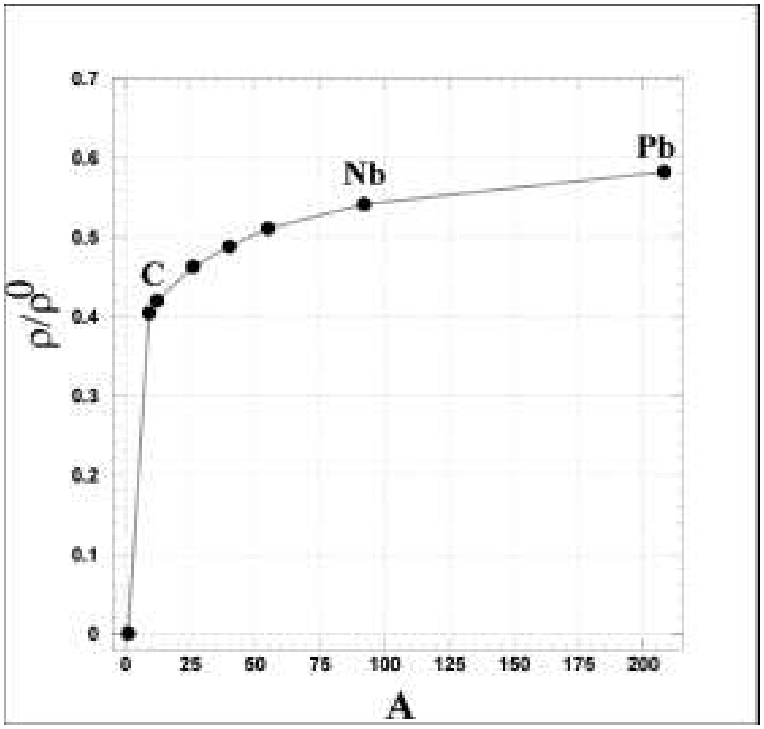

Figure 1: Plot of effective density vs target A.

Issue 2: Uncertainty in the effective density assumed.

Response: With regards to the effective density, the experiment will employ a photon beam which interacts throughout the entire nuclear volume. The measurement averages over the volume so the important information is the average effective density. This quantity is well-known in the nuclear physics community and is confirmed by the state of the art GiBUU model, which is a semi-classical BUU (Boltzmann-Uehling-Uhlenbeck) transport calculation by the Giessen group [4].

Issue 3: Uncertainty in the quantitative understanding of the reaction mechanism.

Response: A photoproduction reaction in nuclei at zero temperature is the preferred experiment. The system is always near equilibrium as opposed to a relativistic heavy-ion collision where the system evolves from high temperature and high density to equilibrium. Moreover, as the result shows, the broadening of the ρ-meson width in the Fe nucleus is indicative of many-body effects which proves that it was formed in the interior of the nucleus. In principle, the production and decay mechanisms are important since the measured mass spectrum is a product of the production cross section, the spectral function, and the decay branching ratio. Each of these quantities is density dependent making the case for more high-quality data. With regards to the branching ratio, the electromagnetic decay is less uncertain which re-enforces our measurement of the e^+e^- channel.

Issue 4: No improvement on the already impressive work of g7a.

Response: To be aggressive and definitive, the medium modifications program with CLAS will produce stringent results in cold nuclear matter unlike any other laboratory in the world. This proposal has been developed since PAC30 to focus on the momentum dependence of the vector meson properties. The data with the CLAS detector will be divided into four bins of e^+e^- momentum to map out the momentum dependence from 0.5 GeV to 3.0 GeV. The total statistical level on the Nb target will increase the precision of the ρ-meson measurement by a factor of 3. The newest addition to the program is a study of the absorption of the ω and ϕ mesons. With the new measurement, the meson absorption will be studied with the entire data set *as well as over multiple momentum bins.* The proposed measurement will break new ground in precision, momentum studies, and absorption studies of the narrow mesons. With the momentum dependence understood, the issue of the existence of mass shifts should be resolved.

1.2 Scheduling Considerations

With the experience and achievements of our results, our group is ready to run the proposed experiment with no major preparation, modification, or new equipment, with the exception of replacing the Pb target foil with Nb and Sn. The Sn target will be thinner than the Nb target and will be used primarily for the absorption studies. All the analysis tools and simulations have been developed and are available allowing physics analysis results within a year. The new g7 experiment will result in important physics conclusions that have not been achieved by other experiments.

2 Physics Motivations

2.1 In-Medium Hadron Modifications

Quantum Chromodynamics (QCD), the theory of the strong interaction, has been remarkably successful in describing high-energy and short-distance-scale experiments involving quarks and gluons. However, applying QCD to low-energy and large-distance-scale experiments has been a major challenge. Although the rapidly increasing strength of the interaction in this latter case makes it impossible to apply perturbative techniques, the symmetries of QCD (such as chiral symmetry) provide guiding principles to deal with strong interaction phenomena. Various QCD-inspired predictions are now available in the non-perturbative domain, which can be tested experimentally at current hadron and electromagnetic facilities.

One of these QCD "inspired" predictions is that in hot (finite temperature) and/or dense (finite density) matter a chiral phase transition takes place, and the broken chiral symmetry is restored resulting in a modification of the properties of hadrons (vector mesons in particular) in nuclear matter from their free-space values. This prediction has generated much interest, and there is an urgent need for experimental data to confirm or refute these predictions in this as yet largely unexplored domain. The first evidence as to the possibility of a medium-lowered ρ meson mass came from the CERES and HELIOS/3 collaborations of CERN in 1995 [5, 6]. The CERES collaboration reported on measurements of low-mass e^+e^- pairs from p-Au and Pb-Au collisions (Fig. 2).Di-lepton spectroscopy allows measurement of the in-medium properties without distortion due to final state interactions (FSI). While their proton-induced data could satisfactorily be accounted for by summing various hadron decay contributions, an enhancement over the hadronic contributions was observed for the Pb-Au data in the mass range between 300 and 700 MeV/c^2. The same year, theorists were able to account for this excess by using a relativistic transport model assuming a drop in the mass of the ρ meson [7]. It has been suggested that traditional effects, such as an in-medium modified pion dispersion relation, may be able to provide enough enhancement [8, 9]. A better understanding of hadron properties in a hot and/or dense environment is therefore one of the most important endeavors of hadronic physics today. The change of properties of the vector mesons in the medium is a hot topic that is currently being studied at RHIC (BNL) [10, 11] and HADES (GSI) [12] and will be studied at ALICE (CERN) by measuring low mass di-lepton production. Although vector mesons preferentially decay into pseudoscalar mesons, the large final state interactions of these mesons with the nuclear medium makes it almost impossible to derive any direct information about the vector meson

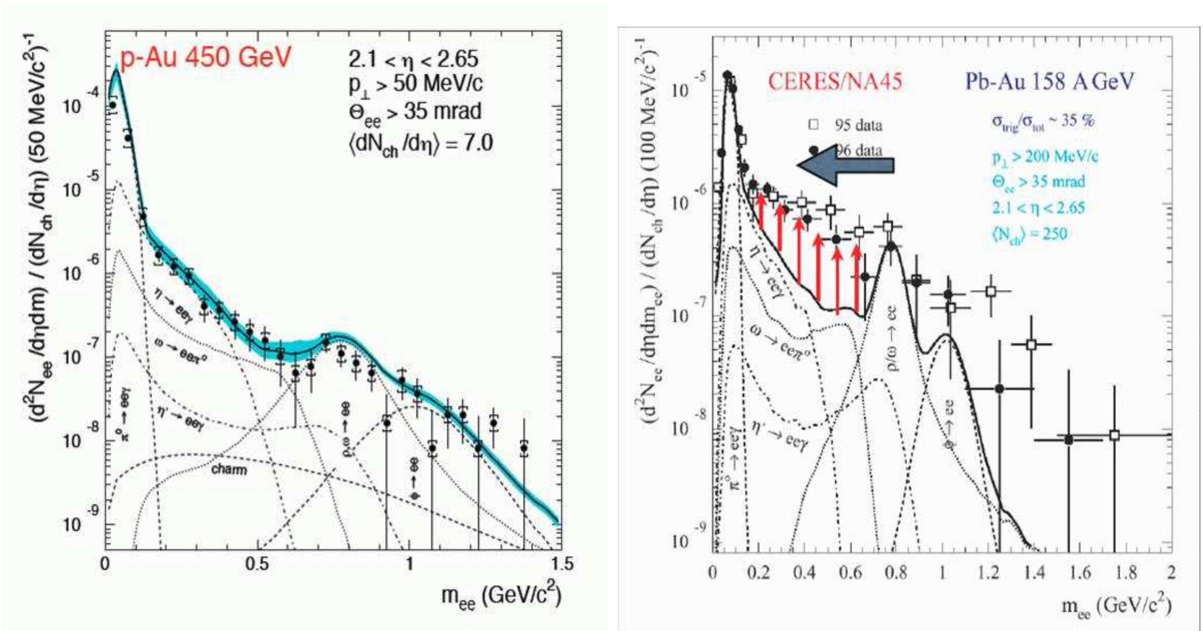

Figure 2: CERES result. Inclusive e^+e^- mass spectra in 450 GeV p-Au (left) and 200 GeV Pb-Au (right) collisions showing the data (full circles and open squares) and the calculations for various contributions from hadronic decays. The shaded regions indicate the systematic error on the summed contributions. Data from Ref. [5].

properties in the medium. In a heavy-ion collision the final di-lepton yield is obtained by an integration over different densities and temperatures, and a discrimination between different scenarios of the in-medium modifications for the vector mesons is difficult. In their initial stages, relativistic heavy-ion reactions originate far from equilibrium and the temperature and density evolve over time. However, all theoretical predictions of in-medium properties of vector mesons in photon- or pion-induced reactions allow one to study the hadron properties in an environment that is much closer to equilibrium (normal nuclear density and zero temperature). The predicted in-medium effects for the vector mesons by the different models are so large that they should have observable consequences already at normal nuclear density. The g7 experiment at JLab is ideal to measure the photoproduction of vector mesons off nuclei and will give complementary information about the in-medium properties of mesons.

2.2 Predictions of Theoretical Models

Due to chiral symmetry restoration, the mass and width the properties of the vector mesons, ω, ρ, and ϕ, are predicted to change with increasing density. Brown and Rho [2], starting from

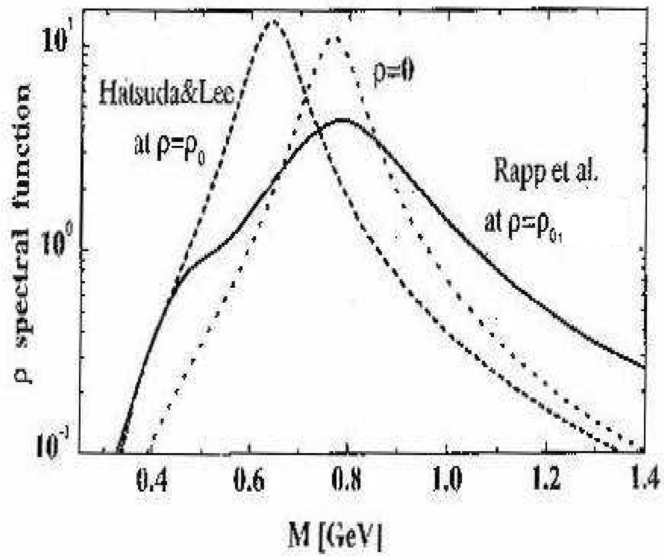

Figure 3: Prediction of Hatsuda and Lee [3] (dashed line) and Rapp *et al.* [14] (solid line) for the mass of the ρ meson at $\rho = \rho_0$ compared to the mass of the ρ meson at $\rho = 0$ (dotted line).

an effective Lagrangian approach at low energy and zero density, suggest the same Lagrangian at high density, but with masses and coupling constants that are modified according to the symmetry constraints of QCD. They proposed an in-medium scaling law that predicts a decrease in the mass of the vector meson by about 20%:

$$\frac{m_{VM}(\rho_0)}{m_{VM}(\rho = 0)} = 0.8, \tag{1}$$

where m_{VM} is the mass of the vector meson, ρ_0 indicates nominal nuclear density (0.16 fm^{-3}), and $\rho = 0$ indicates the vacuum.

Hatsuda and Lee [3], based on QCD sum rule calculations, obtained the spectral changes of the vector mesons in the nuclear medium. Their calculations result in a linear decrease of the masses as a function of density:

$$\frac{m_{VM}(\rho)}{m_{VM}(\rho = 0)} = 1 - \alpha\frac{\rho}{\rho_0}, \qquad \alpha = 0.16 \pm 0.06. \tag{2}$$

While these QCD-based models predict a large downward shift of the vector meson masses, models based on more conventional processes [13, 14, 15, 16, 17] such as in-medium re-scattering, predict no change in the vector-meson mass but a substantial increase in the width of the meson.

Models based on nuclear many-body effects predict a broadening in the width of the ρ meson with increasing density. This prediction is based on the assumption that many-body excitations may be present with the same quantum numbers and can be mixed with the hadronic states. This effect can lead to a collisional broadening of the hadrons being considered, or simple many-body effects such as Pauli-blocking [13, 14]. Fig. 3 shows the prediction of Rapp *et al.* [14] compared to that of Hatsuda and Lee [3].

Another recent calculation is based on the modification of the ρ meson self energy due to the coupling to in-medium pions, which has also included finite-temperature effects by evaluating both the pion and ρ meson self-energy diagrams within the imaginary-time formalism [15]. These calculations suggest that the ρ meson width and mass increase with both density and temperature. However, the broadening depends predominantly on the density, whereas the mass shift is manly a temperature effect.

Theoretical calculations also are available in which a chiral unitary approach to pion-pion scattering in the vector-isovector channel is considered [16]. This approach combines constraints from chiral symmetry breaking and unitarity to investigate the ρ meson properties in cold nuclear matter in a non-perturbative couple channels chiral model. The spectral function of the ρ meson for several values of nuclear matter density obtained with this model is shown in Fig. 4. This model predicts a 30-40 MeV upward shift in the mass of ρ meson at $\rho = \rho_0$ and an enhancement in lower mass.

Lutz et. al [17] have made calculations of medium modifications to the ρ and ω mesons. The spectral functions are broadened and the strengths are fragmented leading to a shift in mass. For the ρ meson, there is an enhancement of the width, and a downward shift in energy, due to the mixing with the baryon resonances.

These effects are density dependent, and, if present, should be observed at normal nuclear densities. Consequently, one should be able to observe the medium modifications of the properties of the hadrons in pion-, proton- or photon-induced reactions.

2.2.1 Momentum Dependence in Theoretical Models

In recent years, the theoretical models have begun to study the momentum dependence of the in-medium properties of the vector mesons. Ref. [18] considers the ρ meson as a virtual $\pi^+\pi^-$ pair while Refs. [19, 20] treat the ρ meson with its coupling to resonance-hole states. In all of these calculations, the spectral functions of the mesons are split into the transverse (A^T) and longitudinal (A^L) parts due to the breaking of Lorentz invariance. These spectral functions are calculated in the rest frame of the nucleus with the z-direction defined along

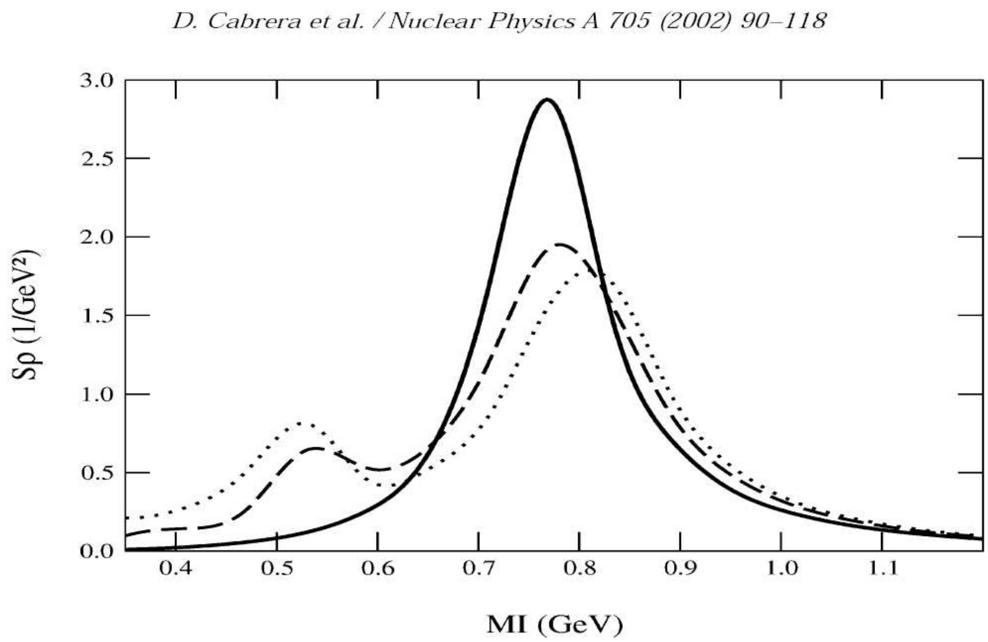

Figure 4: Spectral function of the ρ meson for several values of nuclear matter density. Lines are as follows: solid, dashed, and dottet stand respectively for $\rho = 0$, $\rho_0/2$, and ρ_0 [16]

the momentum of the meson.

Fig 5 shows A^T as a function of ρ-meson mass at normal nuclear density from the calculation by the Giessen group [20]. A comparison is made with various three-momentum of the meson. The momentum range from 0.0 GeV to 0.8 GeV. The calculations are made with two different strengths of the ρN channel. The left plot uses the resonance parameters from Ref. [21] and the right plot uses the parameters from Ref. [22]. The predictions show a strong dependence on momentum. Calculations by Urban et al. [18] predict much smaller modifications in the same momentum range.

2.2.2 Theoretical Models of ω and ϕ Mesons in the Medium

Besides the ρ meson, the theoretical community is investigating the in-medium properites of the ω and ϕ mesons and the absorptive effect in nuclei. With the long lifetimes of these mesons, the medium modifications are studied through the meson-nucleon interaction inside the nucleus. A broadening of the in-medium width increases the meson-nucleon cross section while a lowering of the meson mass raises the number of sub-threshold channels available to the meson. Another effect on the ω and ϕ mesons is the modification of their hadronic components. In the case of the ω, one can consider it as a virtual $\pi\rho$ where both the pion and

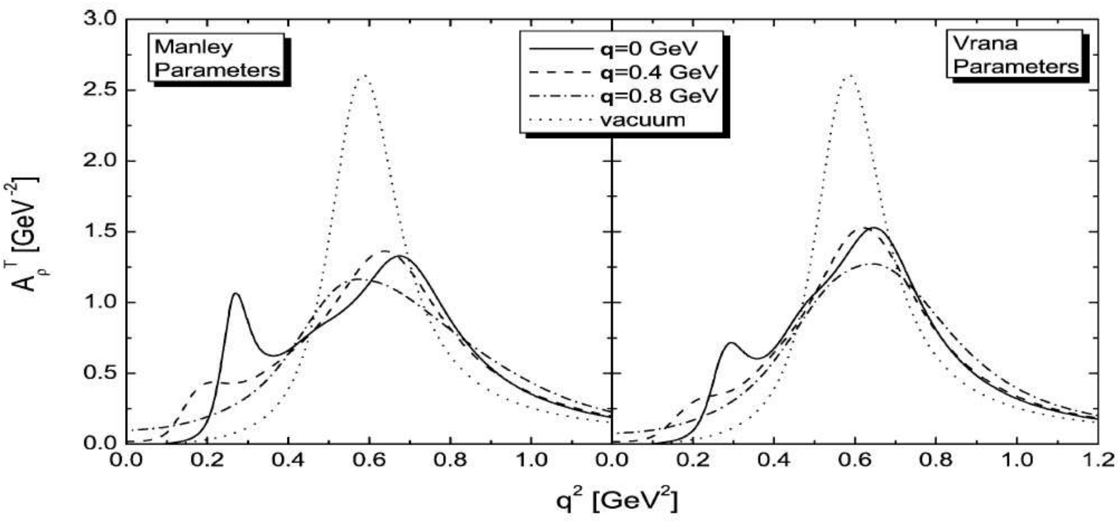

Figure 5: The transverse spectral function versus mass at normal nuclear density. The different momenta of the ρ meson are listed in the legend. The predictions are taken from Ref. [20]. The calculations employ resonance parameters from Ref. [21] (left) and Ref. [22] (right).

the ρ are modified by the medium. For the ϕ meson as a virtual K^+K^- pair, there may be changes to the kaons. These medium effects are discussed in detail by Refs. [23, 24, 25, 26] for the ω meson and by Refs. [27, 28, 29, 30, 31] for the ϕ meson.

Common to all of these calculations is collisional broadening which is discussed here to illustrate how the density and the momentum are related to the meson width. The in-medium width is calculated to be $\Gamma = \Gamma_0 + \Gamma_{coll}$ where Γ_0 is the natural width in vacuum and Γ_{coll} is the width due to collisional broadening. Using the low-density theorem [32], Γ_{coll} has the following relationship:

$$\Gamma_{coll} = \gamma \rho v \sigma^*_{VN}, \tag{3}$$

where γ is the Lorentz factor, ρ is the density, v is the velocity of the meson, and σ^*_{VN} is the meson-nucleon total cross section in the nucleus. Sec. 4.2 will show comparisons of predictions and some data as a means to extract the in-medium widths.

2.3 Existing Data

A large downward mass shift has been reported for the ρ meson by the TAGX collaboration, which used photons incident on a ^{3}He target and detected the $\pi^+\pi^-$ pairs stemming from sub-threshold ρ production [33]. The best fits to their $\pi^+\pi^-$ invariant mass for different photon

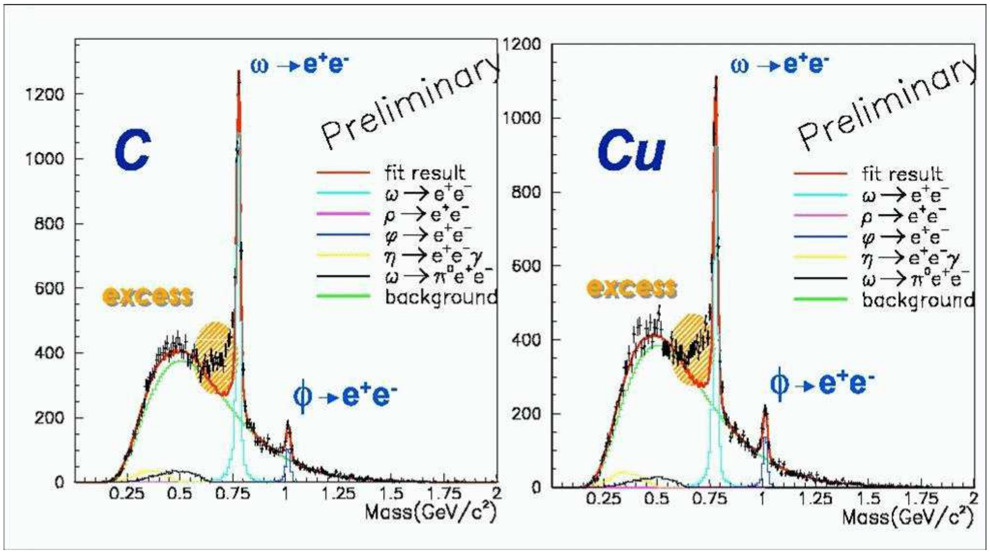

Figure 6: KEK result. Invariant mass spectra of e^+e^- for C (left) and Cu (right) targets. The plots show the best fit results from the mixture of the known hadronic sources and the combinatorial background. Data from Ref. [35].

energies matched to the maximum Brown/Rho shift while a revisited analysis obtained a smaller mass shift [34]. This is a very large effect for a small nucleus such as ^{3}He. Indeed, the $\pi^+\pi^-$ hadronic decay channel is subject to strong final state interactions making the conclusion highly model dependent.

An observation of a medium-modified vector meson invariant mass spectrum has been claimed by a KEK-PS collaboration in an experiment where 12 GeV protons were incident on nuclear targets (C, Cu) and the e^+e^- pairs were detected [35, 36, 37]. Fig. 6 shows the invariant mass spectra of e^+e^- obtained in this experiment. Fits include all the possible physics processes, while the shaded area was excluded from the fit. The background shape was estimated by mixing leptons from different events, while the normalization was obtained as a parameter of the fit. The KEK result is surprisingly compatible with a yield ratio of $\frac{\rho}{\omega} = 0$, that is measured to be unity in p-p scattering [38]. It was claimed that ρ mesons are modified in the medium producing the excess mass seen at the ω peak shoulder. In the latest analysis from the KEK group [37], the $\frac{\rho}{\omega}$ ratio was fixed and a model was used to estimate the probabilities of the decays of ω and ρ mesons inside various nuclei. Based on this model the probabilities of ρ meson decays inside C and Cu targets are 46% and 61% respectively, while those of ω are 5% and 9%. The shapes of the ρ and ω were then changed based on this model and the mass spectra were fit again. Using this method, they obtained the shift parameter of $\alpha = 0.09 \pm 0.002$ (see Fig. 7). Fig. 8 shows the result of the same experiment

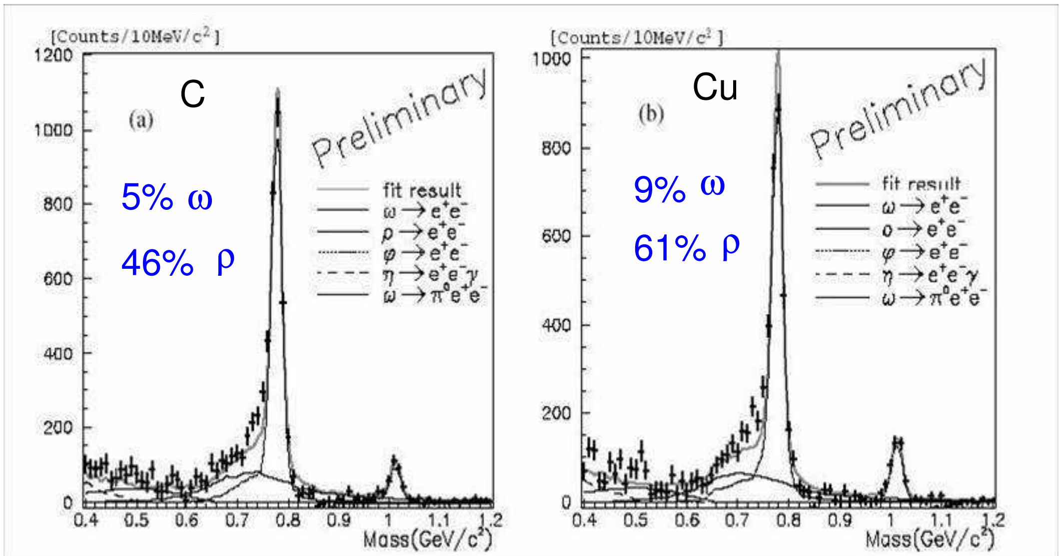

Figure 7: KEK result. Invariant mass spectra of e^+e^- for C (left) and Cu (right) targets after subtracting the background. The shapes of the ρ and ω were changed based on the prediction of a model for the probabilities of the decays of ω and ρ mesons inside a given nucleus. The mass spectra were fit again and the shift parameter of $\alpha = 0.09 \pm 0.002$ was obtained. Data from Ref [37].

for the ϕ meson. It is shown that by selecting low momentum ϕ mesons, the shoulder due to the possibly modified ϕ's decaying in the nucleus can be enhanced. Since few ϕ's decay inside the nucleus, one needs sufficient statistics after the momentum cuts to observe the shoulder.

The Crystal Barrel/TAPS collaboration has reported a downward shift in the mass of the ω, where the analysis focused on the $\pi^0\gamma$ decay of low-momentum ω mesons photoproduced on a nuclear target [39]. The result of this experiment is shown in Fig. 9. The $\omega \to \pi^0\gamma$ channel is a very "clean" channel for studying ω mesons since the branching ratio for $\rho \to \pi^0\gamma$ is two orders of magnitude smaller. Data were taken for two nuclear targets (H_2 and Nb) and compared after subtracting a huge background. An enhancement was found toward lower masses for ω mesons produced on the Nb target. By comparing the H_2 to Nb they found a pronounced modification of the ω meson mass in the nuclear medium with momenta less than 500 Mev/c. One serious concern about this experiment is the possibility of the π^0 re-scattering in the nuclear medium which could distort the invariant mass spectrum. Recently, a concern has been raised about the background substraction [40]. A slight change in background subtraction could change their results significantly.

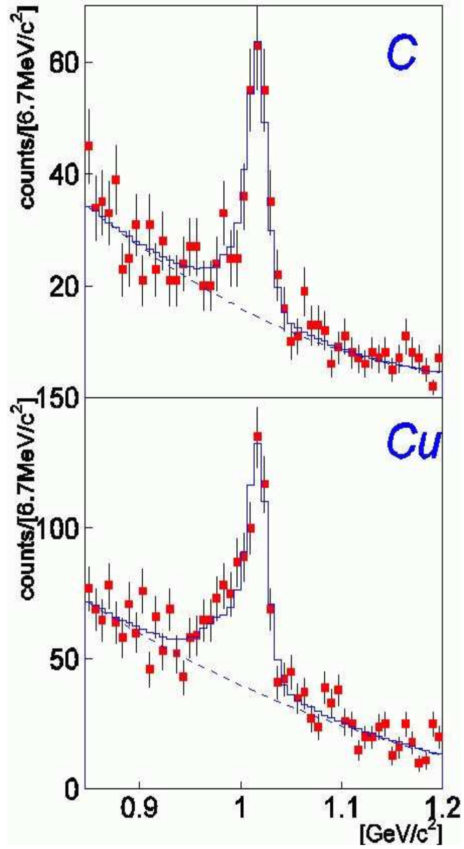

Figure 8: KEK result. Invariant mass spectra showing the low-energy ϕ mesons for C (top) and Cu (bottom) targets. The dotted lines represent the quadratic background curve. Data from Ref [36].

A recent PHENIX experiment at RHIC also was performed to measure di-leptons in Au+Au collisions [11]. The invariant mass spectrum was compared to the expectation from hadronic decays. However, the small signal to background ratio, sparse data, and large statistical uncertainties make any physics conclusions impossible.

Recently, the NA60 experiment at the CERN SPS has studied low-mass muon pairs in 158A GeV In-In collisions [42]. A strong excess of $\mu^+\mu^-$ pairs is observed above the expectation from the neutral meson decays. The high statistics and good mass resolution of about 2% have allowed them to isolate the excess by subtraction of the known sources. The shape of the resulting mass spectrum is consistent with a dominant contribution from $\pi^+\pi^- \to \rho \to \mu^+\mu^-$ annihilation. The associated ρ spectral function compared to the prediction of Rapp/Wambach for broadening, and that of Brown/Rho for the shift in the mass of the ρ, shows no shift in mass but broadening in the width of the ρ (Fig. 10) [14]. However, in their recent paper, Brown and Rho have pointed out that the comparison between the recent

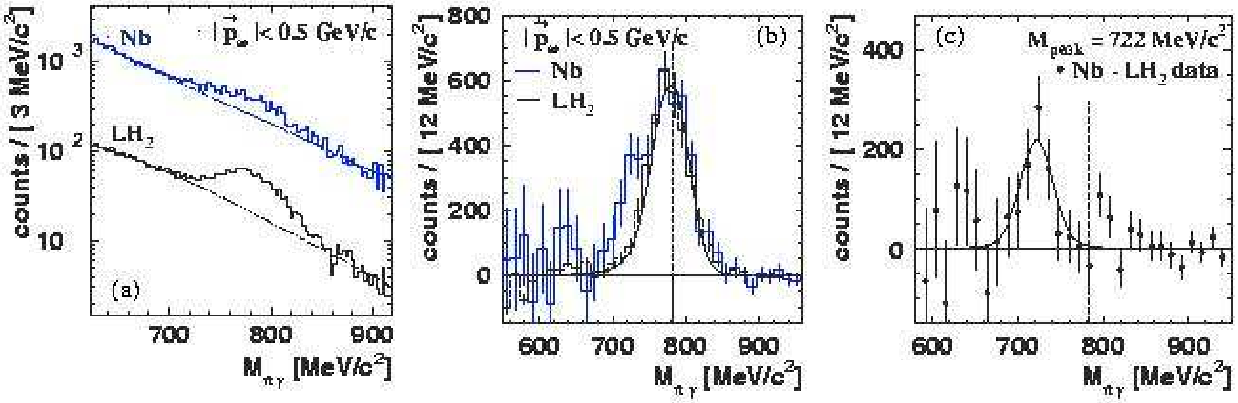

Figure 9: (a) Crystal Barrel/TAPS result. Inclusive $\pi^0\gamma$ invariant mass spectra for ω momenta less than 500 MeV/c. Upper histogram: Nb data, lower histogram: LH_2 target reference measurement. The dashed lines indicate fits to the respective backgrounds. (b) $\pi^0\gamma$ invariant mass for Nb data (solid histogram) and LH_2 data (dashed histogram) after background subtraction. The error bars show statistical uncertainties only. The solid curve represents the simulated line shape for the LH_2 target. (c) In-medium decays of ω mesons along with a fit to the data. The vertical line indicates the vacuum ω mass of 782 MeV/c^2. Data from Ref. [39].

NA60 di-μ data as presented is not founded on a correct interpretation of the prediction of Brown and Rho scaling as formulated in 1991 and modernized recently. Hence they state that the conclusion drawn by the NA60 group is erroneous [43]. Furthurmore, the extracted ρ spectrum in NA60 experiment is so wide that makes any definitive conclusion on the mass shift difficult.

The latest medium modification results reported by RHIC experiments are not consistent with the KEK and TAPS conclusions. In heavy-ion reactions, the final e^+e^- yield is the result of contributions from different densities and temperatures; thus a discrimination between different scenarios of in-medium modifications for vector mesons is difficult. The study of the density-induced modifications on the properties of vector mesons has seen much theoretical and experimental interest. Experiments such as g7 that look for medium modifications in normal nuclear density at equilibrium are needed to disentangle the different mechanisms [43]. The recently published g7 results [1] (also see Sec. 3) has also provided precision measurement that can be used to constrain theoretical models and shed light on the relation between the chiral symmetry restoration and mass spectra observed in experimental data.

At this time, there are no published results of the momentum dependence of the in-medium properties of the ρ, ω, and ϕ mesons. The experiment described in this proposal will be the first to address this important and timely issue.

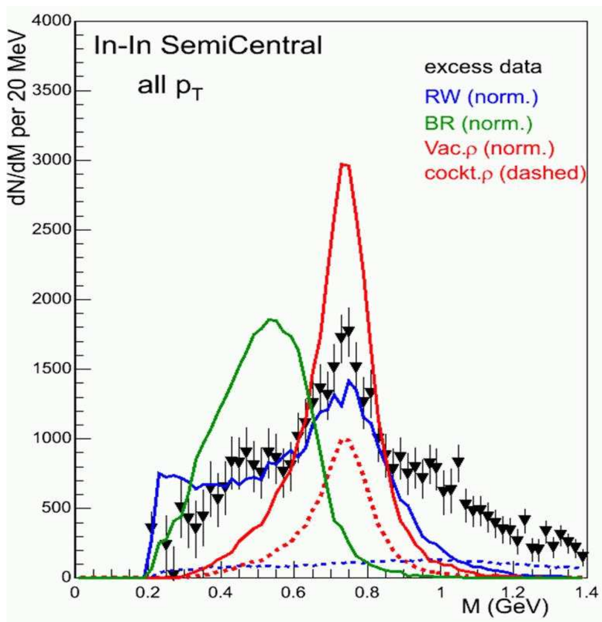

Figure 10: NA60 result. The result of di-μ analysis at the CERN SPS. Comparison to model predictions: unmodified ρ (red solid), prediction of Rapp/Wambach [14] for in-medium broadening of the ρ (blue solid), in-medium shift by Brown and Rho [2] (green solid), the cocktail (red dashed), and the level of combinatorial charm (blue dashed). Data from Ref [42].

3 The g7a Results

The g7a results on the medium-modifications search of the ρ meson have been been published and can be found in Ref. [1]. A longer article for Phys. Rev. C is currently under review by the CLAS ad hoc committee. This section will summarize the findings and show the high-quality of the measurement with the CLAS detector.

The clear peaks of ω and ϕ mesons can be recognized in the e^+e^- invariant mass spectrum. It is also shown that the yields of the ω and the ϕ decrease with increasing target density (Figs. 11). Any medium-induced shift in the mass or change in the width of the ρ meson, is determined solely from the comparison of the data from different targets.

Contributions from the ω and ϕ mesons as well as a mixed-event background were subtracted from the data to extract the experimental spectra of the ρ mass. The mixed-event background was determined by a well-known technique which is discussed in the g7a Analysis Note [1, 47]. The GiBUU model [4] is used only to generate and subtract the shapes of well known channels that are not the main subject of this study. The extracted ρ mass distributions are then fit with the suggested functional form of $1/m^3$, where m is the pole mass, times the Breit-Wigner function rather than a simple Breit-Wigner distribution [2] [48, 49, 50]. Fig. 12 gives a comparison of the two fits to the ρ mass shape from the ^{2}H target. The extracted ρ mass distributions for various targets are shown in Fig. 13. The Breit-Wigner/m^3 fits describe the data very well, and the width of the ρ meson is consistent with the natural width of 150 MeV. This is not compatible with the doubling of the ρ width reported by NA60 [42]. It is important to mention that in the analysis of KEK [35, 36, 37], they were not able to directly extract the ρ signal.

A study of the ratio of the ρ mass distributions for Fe to ^{2}H and C to ^{2}H targets is a clean model-independent method to measure a possible shift in the mass of the ρ. The analysis of the ratios of the mass spectra is given in the appendix and in Ref. [47]. Table 1 lists the extracted pole masses and widths of the ρ meson in the different targets.

The data show no large change to the pole masses and a broadening of the widths as the effective density of the target increases. A simulation was performed with the GiBUU model without including any mass shifts including many-body effects such as Fermi motion, shadowing, and collisional broadening. The conclusion from the comparison with the simulation is that the broadening in the ρ-meson width is due to many-body effects. The

[2] In the dilepton emission diagram there is a photon line that gives the dilepton pair. The corresponding propagator has the form of $1/q^2 = 1/m^2$. This term contributes as $1/m^4$ in the cross section while the phase space also gives a factor of m resulting to a $1/m^3$ factor [51].

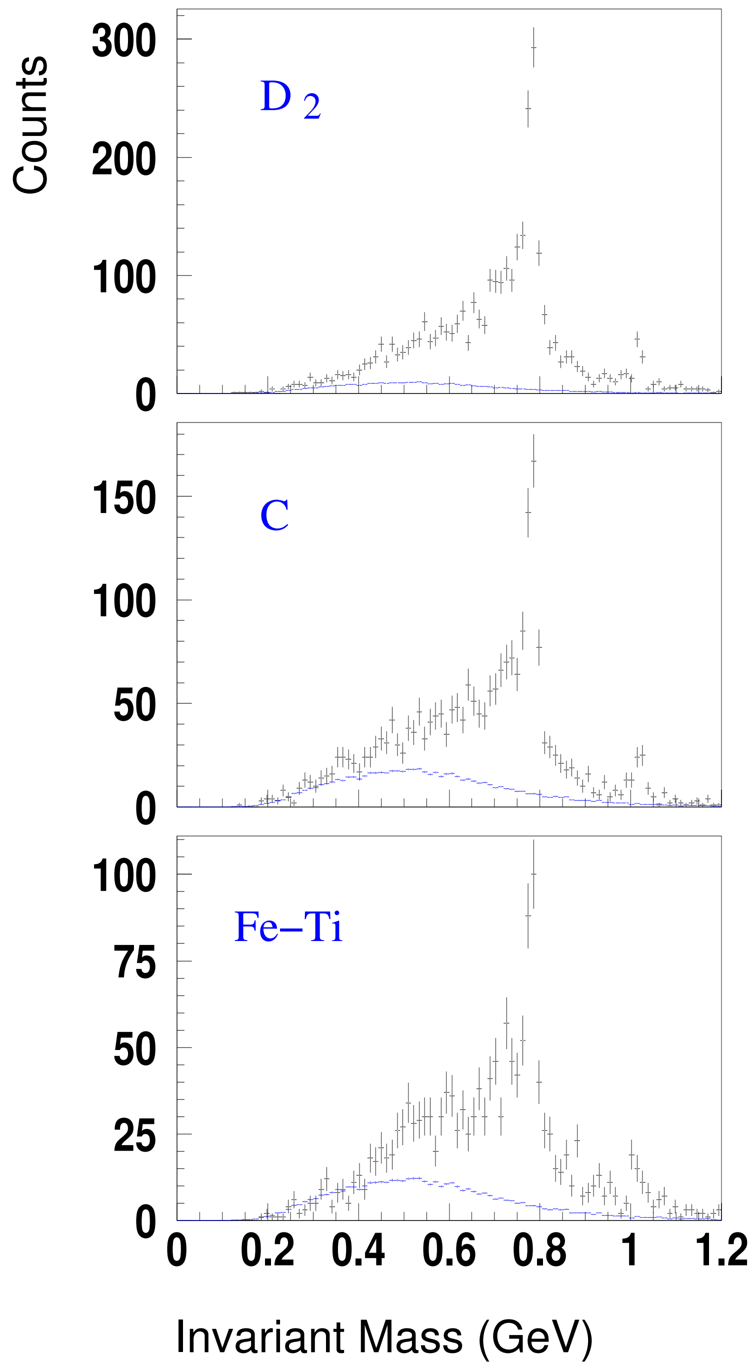

Figure 11: Plot of the e^+e^- invariant mass spectra with mixed-event background for deuterium (top), carbon (middle), and iron (bottom) targets. The mixed-event background is shown in blue.

simulation cannot treat the nuclear effects of deuterium. Instead, it models the deuteron as a free proton and neutron. To avoid confusion, the information of deuterium from the

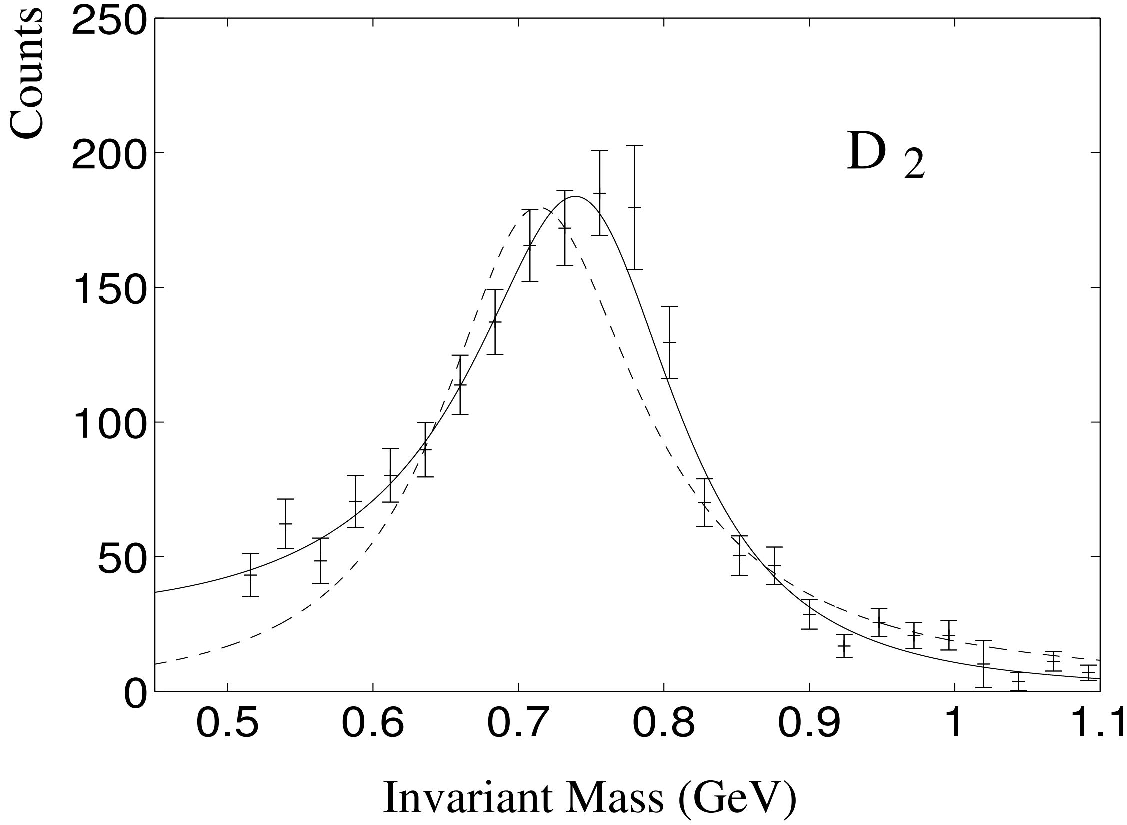

Figure 12: Fits to the ρ mass spectrum for the deuterium data using a Breit-Wigner (dashed) and a Breit-Wigner/m^3 function (solid).

simulation is not included in the table. With the g7a data, we determined a mass shift of 8±8 MeV in Fe (consistent with zero) corresponding to $\alpha = 0.02 \pm 0.02$ ($\Delta\alpha \leq 0.053$ within a 95% confidence level).

Table 1: The pole mass and width of the ρ meson obtained from the simultaneous fits (M_{exp},Γ_{exp}) to the mass spectra for each target and the ratio to ^{2}H compared to the result of the simulations (M_{sim},Γ_{sim}). The masses and widths are consistent with the natural values [52] (770.0 ± 0.8 MeV and 150.7 ± 1.1 MeV, respectively) adjusted for the collisional broadening. The units are in MeV.

Target	M_{exp}	Γ_{exp}	M_{sim}	Γ_{sim}
^{2}H	770.3 ± 3.2	185.2 ± 8.6	-	-
^{12}C	762.5 ± 3.7	176.4 ± 9.5	773.8 ± 0.9	177.6 ± 2.1
^{56}Fe	779.0 ± 5.7	217.7 ± 14.5	773.8 ± 5.4	202.3 ± 11.6

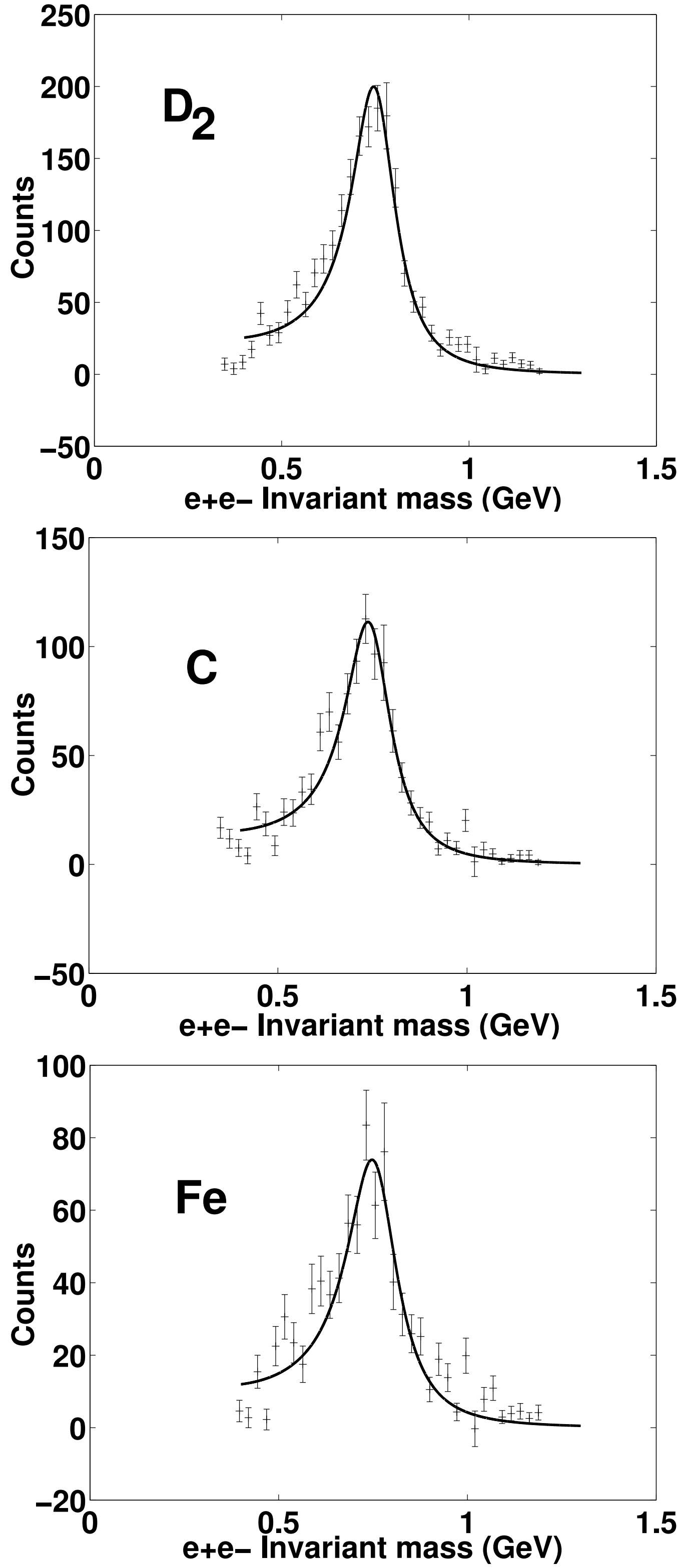

Figure 13: Extracted ρ mass distributions (GeV) for various targets from the g7a data. Fits of the form of $1/m^3$ times the Breit-Wigner function ([48, 49, 50]) describe the data well.

3.1 Advantages of the Proposed Experiment

At JLab energies, photoproduction of ρ-mesons off heavy nuclei is the ideal way to determine any modification of the meson properties in nuclear matter. A larger fraction of the produced ρ mesons decay inside the nuclear targets due to their small life time ($c\tau_\rho = 1.3$ fm), compared to the ω ($c\tau_\omega = 23.4$ fm) and ϕ ($c\tau_\rho = 44.4$ fm) mesons. Due to their electromagnetic character, di-leptons leave the interaction region without further strong interactions, and thus carry undistorted information of the dynamical properties of the system. Because vector mesons preferentially decay into mesons, the large final state interactions of the mesons with the nuclear medium makes it almost impossible to derive any direct information about the vector meson properties in the medium. The GiBUU calculation by Effenberger and Mosel indeed shows that the $\pi^+\pi^-$ invariant mass spectrum exhibits almost no sensitivity to medium modification of the ρ meson [4]. Even though the branching ratio to e^+e^- is $\approx 5 \times 10^{-5}$, the predicted in-medium effects for the vector mesons by the different models are so large that they have observable consequences even at normal nuclear density. This transport model is an important step toward a consistent theoretical description of vector meson production, propagation, and decay in the nuclear medium. This model calculates inclusive particle production in heavy-ion collisions from 200A MeV to 200A GeV in photon and in pion-induced reactions with the very same physical input. This model has been used to give predictions for di-lepton production in πA reactions that will be measured by the HADES collaboration [44, 45].

The experiment has the advantage of using a photon beam to produce and study the in-medium properties of vector mesons that provides minimum perturbation in the incoming channel. Furthermore, the photoproduction of the vector mesons takes place throughout the nucleus. Unlike the TAPS experiment, all three vector mesons are present in this single measurement.

With our understanding of the background, we are able to cleanly extract the experimental mass distribution of the vector mesons. By comparing the extracted experimental ρ mass spectra for C and Fe to ^{2}H targets, we have been able to rule out any mass shift greater than $\alpha = 0.053$ with a 95% confidence. In addition to the momentum dependence, we will be able to give a quantitative measure of smaller medium modifications, if there are any, given the increased statistics of the new experiment. We anticipate a sensitivity on the order of ± 0.007 in the measurement of the ρ mass shift parameter α in Nb target over the entire momentum range (see Appendix A).

In the new experiment, the $A(\gamma, e^+e^-)A'$ reaction will be measured by identifying the

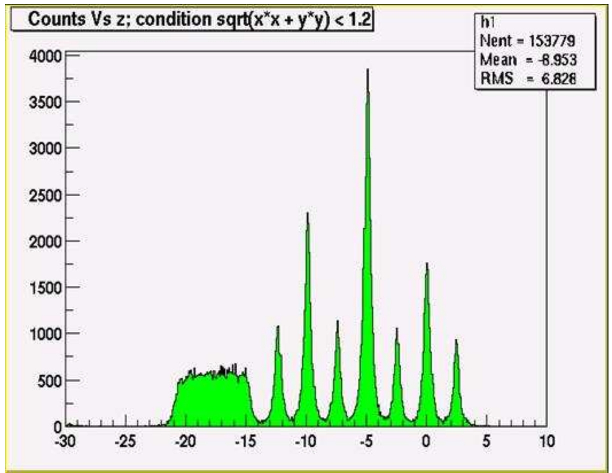

Figure 14: The distribution of the z-component of the reconstructed vertex position for the g7a data. The CLAS vertex reconstruction resolution is about 0.3 cm.

coincident electron/positron pairs in the CLAS detector. Energy deposition in the electromagnetic calorimeter and the Cerenkov counter signal define clear cuts for the separation of the e^+e^- events from the very large hadronic background. To minimize systematic errors, the solid targets will be divided into several parts, and the separation between adjacent targets (2.5 cm) will be matched to the CLAS vertex reconstruction resolution which is 0.3 cm (see Fig. 14).

In the previous experiment, the data were taken on four nuclear targets simultaneously: deuterium, carbon, iron and lead with a beam intensity of 5×10^7 tagged photons per second in the energy range from 1.2 to 3.8 GeV. Setting the magnetic field of the CLAS detector to half its maximum value at nominal polarity was found to be optimal for this photon energy range. At this field setting the yield of the low momentum e^+e^- pairs is optimized to the momentum resolution of CLAS. Tagged photons were used to determine the kinematics of the reaction. In the off-line analysis, the e^+e^- mass spectra are analyzed under different kinematical conditions. Bethe-Heitler (e^+e^-) background is drastically reduced by the acceptance of CLAS. Extensive simulations show that the acceptance of CLAS does not introduce an experimental distortion of the invariant mass spectrum of the detected e^+e^- pairs.

Theorists such as U. Mosel at Giessen, M. Soyeur at Saclay and E. Oset at Valencia, have done extensive work on medium modifications of vector mesons, and are interested in the new proposal. Extensive GiBUU calculations has been done to optimize the choice of target nuclei. The proposed experiment does not require high beam energy. The data reduction and analysis can be done rapidly since all the analysis tools have already been developed.

The experiment is part of a larger program at Jefferson Lab. Recently, JLab proposal E05-110 in Hall A was approved with an A- rating to study the modification of the properties of the nucleon in the nuclear medium. This Hall A approved experiment aims to investigate the properties of nucleons inside nuclei via quasi-elastic scattering off nuclei and to study the charge and magnetic responses of a single nucleon [46].

The new experiment will be built on the success of the previous measurement and will produce results much quicker. Our group has experience with nuclear targets and e^+e^- detection with the CLAS detector. Extensive work has been done with the pair identification software and with the simulation program of vector meson production in nuclei. The amount of development in hardware and software will be minimal. The tools have been developed and refined.

4 New Measurement

The g7a data have already placed a stringent upper limit on the mass shift. The next step is to study if there is a breaking of Lorentz-invariance associated with the in-medium properties of the ρ, ω, and ϕ mesons. This investigation can be made by measuring the momentum dependence of the in-medium properties. The new experiment will answer the question as to whether the in-medium properties of the vector mesons remains constant over a range of momentum or if the medium modifications evolve from low to high momentum.

All three vector mesons will be studied for in-medium effects with respect to momentum. The ρ meson will provide information about changes to its mass and width from its decay inside the nucleus. The ω and ϕ mesons will access changes to the widths from their interactions with nucleons as the mesons escape from the nucleus. All of these measurements will benefit from heavier targets of Nb and Sn.

4.1 Momentum Dependence

Fig. 15 shows the momentum distribution for e^+e^- pairs from the g7a data and scaled by a factor of 5 to the expected statistics from the new experiment. With this number of events, the data will be divided in four bins of an equal number of counts as shown in the figure. The momentum ranges will be 0.5-0.9 GeV, 0.9-1.1 GeV, 1.1-1.45 GeV, and 1.45-3.0 GeV. Each of these bins will have the sensitivity to changes to the in-medium properties as the g7a measurement. Fig. 16 shows the expected statistical level of the ρ-meson mass spectrum with the Fe target in one momentum bin. The data are the spectrum from the previous measurement. The curve overlayed in the figure is the theoretical prediction of the transverse spectral function at meson momentum of 0.4 GeV [20].

With the techniques developed for the g7a analysis, an e^+e^- mass spectrum will be produced for each momentum bin. Due to the low statistics of the g7a experiment, a momentum analysis is not possible with the existing data. The mixed-event background will be determined and subtracted for each momentum sample. After removing the ω and ϕ contributions, the ρ signal will be all that will remain in the mass spectra. With data on ^{2}H, Fe, Nb, and Sn targets, the pole mass and width of the ρ meson will be extracted in a model-independent way. These new data with the proven analysis procedure will confirm any connection between momentum and predicted medium modifications.

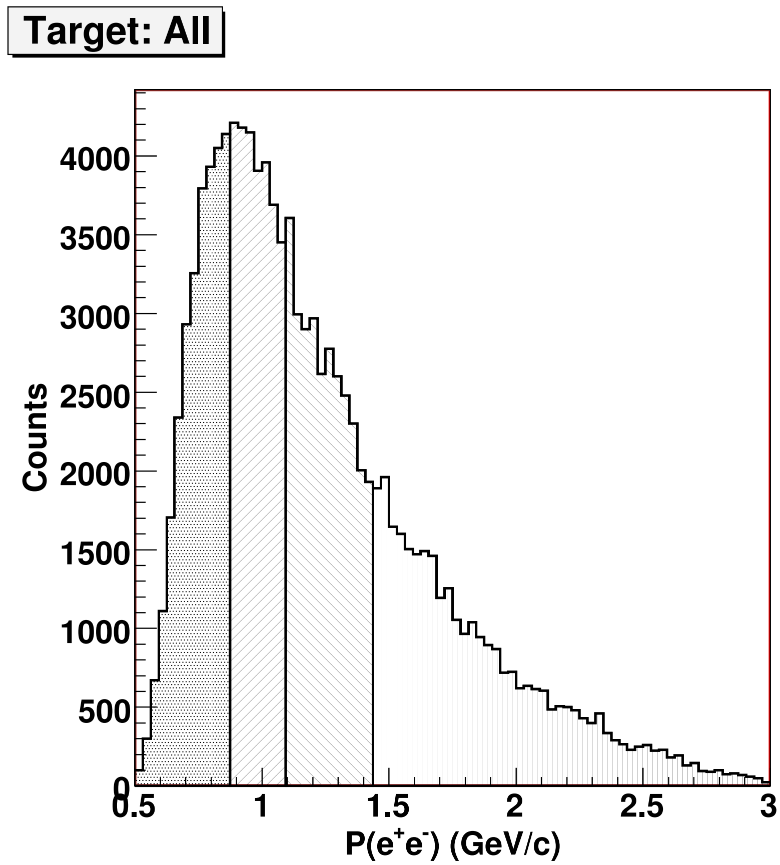

Figure 15: Plot of e^+e^- momentum divided in four bins of equal statistics.

4.2 In-medium Widths of the ω and ϕ Mesons

With momenta greater than 0.5 GeV and their long lifetimes, the ω and ϕ mesons are expected to escape the nucleus and decay in the vacuum. These facts make them unlikely candidates for medium modification studies. However, as these mesons travel through the nucleus, there is a probability for a secondary interaction with a nucleon. The ω-N and ϕ-N reactions bring about a depletion in the number of detected vector mesons. By measuring the survival probability, the in-medium properties of the ω and ϕ mesons can be extracted [23]. From an optical model of the ω and ϕ meson scattering in nuclei, the change in the width is proportional to the imaginary part of the scattering amplitude, which can be extracted from the data easily. This approach of using the absorption to access the in-medium widths of the ω and ϕ mesons has developed recently [23, 24, 25, 26, 27, 28, 29, 30, 31]. In the absorption analysis, the transparency employed to gauge the nuclear effects on the mesons

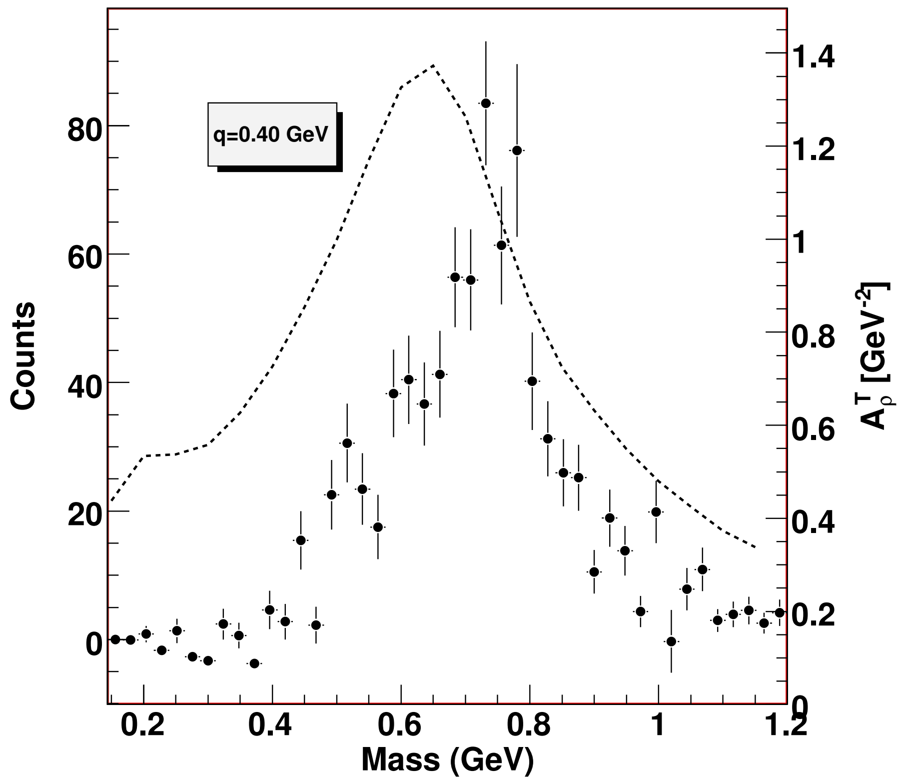

Figure 16: Plot of expected statistical precision for one momentum bin with the Fe target. The circles are the ρ-meson mass for Fe data from the previous measurement. The curve is the predicted transverse spectral function with a meson momentum of 0.4 GeV (dashed) taken from Ref. [20]. The axis on the right corresponds to the theoretical curve.

and is defined as

$$T_A = \frac{\sigma_A}{A\sigma_N}, \tag{4}$$

where σ_A and σ_N are the nuclear and nucleon total cross sections, respectively.

The TAPS coolaboration is presently analyzing the ω meson data which were collected to determine a mass shift [41]. That measurement has determined an in-medium width of the ω meson of about 95 MeV by comparing with recent calculations from the Giessen group [23]. The TAPS data are shown with the blue triangles in Fig. 17 while the predictions are the curves in the left plot. In the right plot, predictions by the Valencia group [24, 25] are shown with the curves along with the TAPS data. The red squares are the preliminary results from the g7a data which indicate a much larger broadening of the widths.

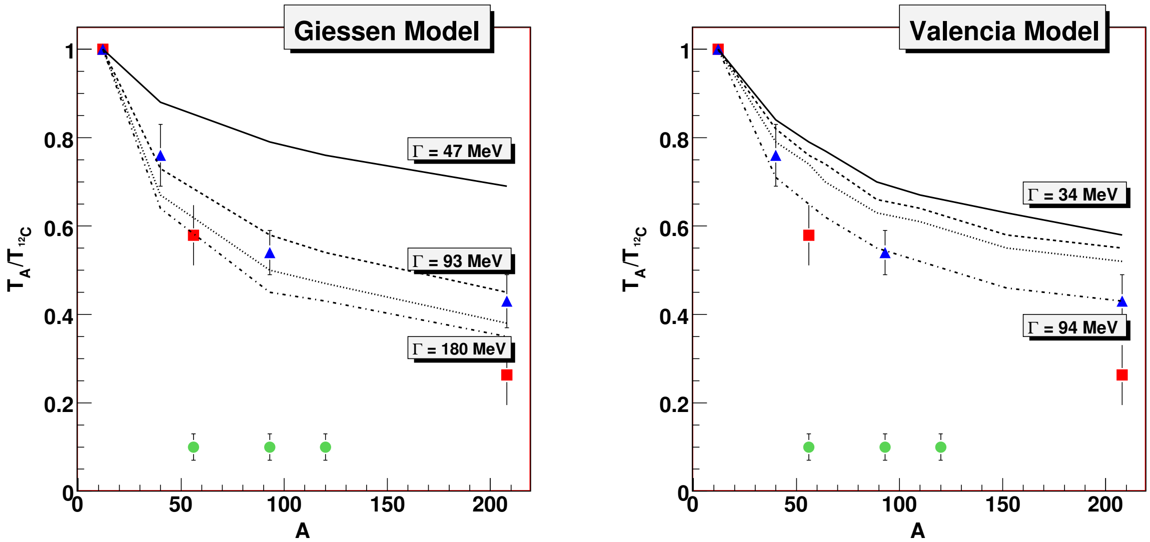

Figure 17: Transparency ratio for ω meson. The results are normalized to the carbon transparencies. The blue triangles are TAPS data from Ref. [41]. The red squares are preliminary results from the g7a experiment. The curves are the calculations from the Giessen group [23] (left plot) and the Valencia group [24, 25] (right plot). The green circles show the expected errors with the Fe, Nb, and Sn targets from the proposed experiment.

With respect to the ϕ meson, photoproduction data exists from SPRING8 [53] where the ϕ mesons was reconstructed from its decay in K^+K^-. These data are shown in Fig. 18 along with calculations from the Giessen group [27]. The red squares are the preliminary data from the g7a experiment which shows better agreement than in the case of the ω meson.

With the statistical level of the new experiment, the transparency ratios will be extracted in the four bins in e^+e^- momentum. The in-medium broadening of the ω- and ϕ-meson widths will be analyzed as a function of momentum. The transparency ratios will be determined with the Nb and Sn targets. These data will fill in the large gap between the Fe and Pb results. Moreover, a direct comparison can be made with the TAPS data which include a data point with Nb.

4.3 Heavier Target

With the present g7a result in the search for medium modifications of the ρ meson, there is just the one data point with the Fe nucleus. Data with a Fe target will link the new measurement to the g7a result; however, data with heavier nuclei is warranted. The additional targets for the new experiment will be Nb and Sn. There will be a 10% increase in average

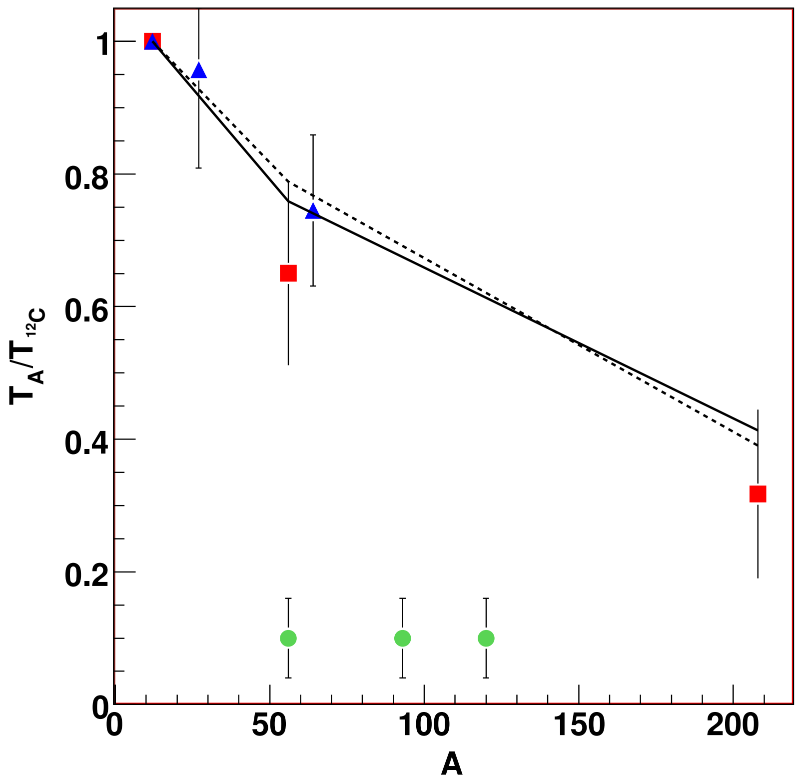

Figure 18: Transparency ratio for ϕ meson. The results are normalized to the carbon transparencies. The blue triangles are the SPRING8 data from Ref. [53]. The red squares are preliminary results from the g7a experiment. The curves are the calculations from the Giessen group [27]. The green circles show the expected errors with the Fe, Nb, and Sn targets from the proposed experiment.

effective density as shown in Fig. 1 and discussed in Sec. 1.1. When the data is analyzed over the entire momentum range, a sensivity to a mass shift of the ρ meson with be about $\Delta\alpha = 0.007$. This value translates to a shift of approximately 3 MeV in Nb.

5 Proposed Running Conditions

The new experiment will require increasing the statistics by a factor of 5 over the previous experiment. This can be achieved by a combination of increasing the instantaneous luminosity and the running time. We plan to increase the integrated luminosity by

- increasing the total target thickness by a factor of 2.5,
- increasing the running time by a factor of two (36 days).

The g7b running conditions will be the same as for g7a:

- Maximum torus setting of 1950A at nominal polarity.
- Minitorus setting of 6000A.
- Photon beam energy of 3 GeV.

5.1 Trigger

The triggers will remain the same as in the previous experiment, which included two lepton triggers. The first trigger was set with two lepton tracks which involved hits coincident in the EC, CC, and SC detectors in two different sectors. The EC and CC components identified the track as a lepton. The SC component guaranteed that the track was charged and rejected accidental photons in the EC and CC [3]. The second trigger was a coincidence in the EC, CC, and SC for one sector, which was set for single lepton events and was employed as a systematic check of accidental leptons. The first trigger is always present in the second trigger. For both triggers, a level 2 condition was applied to require at least one track to be identified by the DC. The level 2 requirement was 3 hits out of 5 DC layers. Figs. 19 and 20 show the single lepton and two lepton trigger rates as a function of the beam current.

5.2 Data Rate

The trigger rates from the first experiment were about 180 Hz for the two lepton trigger and 800 Hz for the single lepton trigger (see Figs. 19 and 20). The maximum rate of the Hall B data acquisition (DAQ) system has increased to at least 8 kHz. The improved DAQ rate and low lepton-trigger rates provide room to increase the data rate for the proposed experiment. We propose to increase the instantaneous luminosity by a factor of 2.5. From

[3] The trigger requirement was 3 out of 4 EC-CC elements.

the nearly-linear behavior in Figs. 19 and 20, the lepton-trigger rates are not expected to be dominated by accidentals. For the previous experiment, the average hit occupancy in each Region 1 sector in CLAS was about 1.2%. Scaling the data rate by this factor will keep the DC occupancy at or below 3% which is within the operating limits of the CLAS detector.

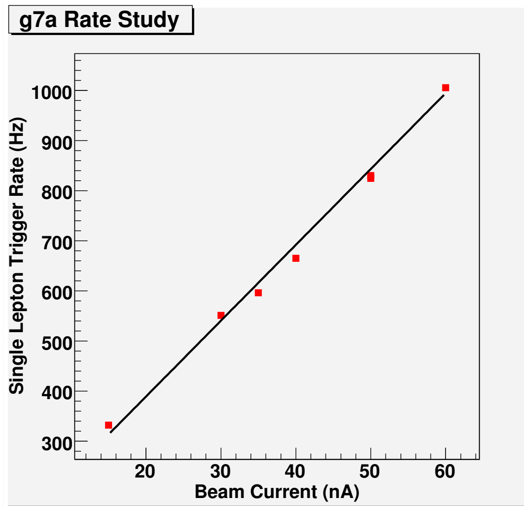

Figure 19: Single lepton trigger rate for the g7a data as a function of beam current. The line is a linear fit to the data.

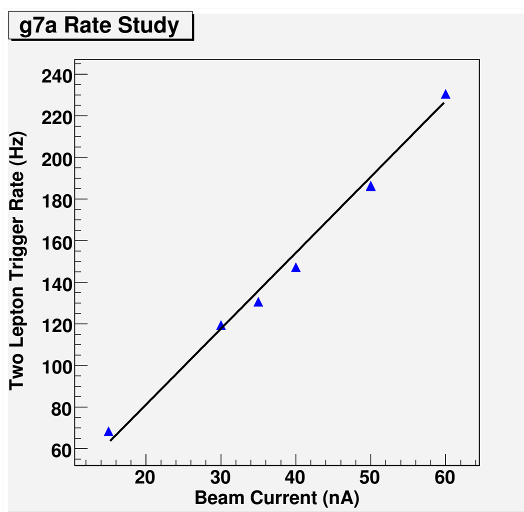

Figure 20: Two lepton trigger rate for the g7a data as a function of beam current. The line is a linear fit to the data.

5.3 Target Geometry

The multi-segment target contains material with different average densities. In the previous measurement, it consists of a cell of liquid deuterium and seven solid thin foils of C, Fe, Ti, and Pb, that each contain 1 g/cm^2 of material. Four carbon targets were used to study the effect of vertex position and CLAS acceptance. The vertex position is well-known after the previous experiment. For the proposed experiment, we will use C, Fe, Nb, and Sn. By repeating the Fe measurement, we will be able to link to the earlier result and add confidence to the new measurement. Replacing Pb with Nb will significantly reduce the background by almost half, and increase the sensitivity in the measurement of the shift parameter α. The ^{2}H target will still be used since the small ^{2}H nucleus is a good reference where no major density-dependent effect is expected. The ^{2}H target has contributions from both the proton and the neutron compared to ^{1}H and includes some Fermi motion inside. Furthermore, the same amount of ^{2}H takes less space than ^{1}H and allows enough space in the scattering chamber to put the other solid foils and separate them sufficiently to avoid multiple scattering effects. The Fe and Nb targets will be divided in three foils each with the Nb foils downstream of the Fe foils. Fig. 21 illustrates the layout of the proposed target arrangement. A thinner foils of C and Sn will be added for the ω and ϕ absorption measurements. The Sn target will be needed to fill the gap in the transparency ratios between Fe and Pb (see Sec. 4.2). The C target is needed for normalization to a nucleus with a small radius. The thickness of each target will be set to have an increased luminousity of a factor of 2.5 over the previous experiment.

5.4 Expected Invariant Mass Distribution

Increasing the statistics by a factor of 5 will increase the amount of correlated e^+e^- pairs by a factor of 5. However, the uncorrelated background will increase by a factor of 10. This is due to the fact that increasing the luminosity by a factor of 2.5 will increase the uncorrelated background by a factor of 6.2, while increasing the running time increases the amount of background by an additional factor of 2. Fig. 22 shows the expected invariant mass distribution obtained from the simulation for an Fe target with five times more statistics. The expected uncorrelated background is also shown in the same figure. The ratio of the ρ signal to the uncorrelated background is estimated to be at the level of one to one. The shape and normalization of the background will be determined using the mixed-event technique [47]. The procedure for determining the mixed-event background is quite robust. The technique

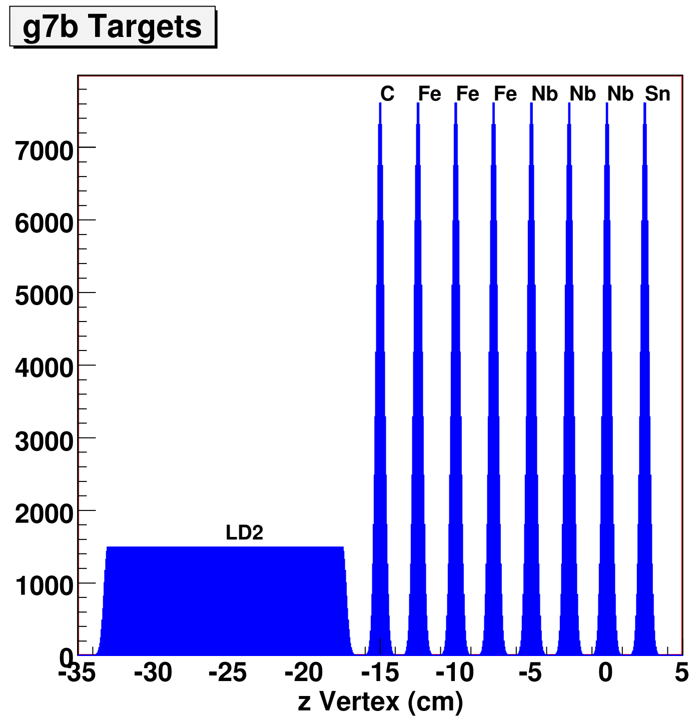

Figure 21: Sample target assembly for the new experiment.

has been very successful with the PHENIX experiment [11] where the signal over the background is 1%. The new data are expected to provide a more accurate estimation of the uncorrelated background because of the higher statistics of the same-charge events.

5.5 Beam Time Request

We request 36 days of beam time for the proposed experiment. The goal of this experiment is to increase the integrated luminosity by a factor of 5. The CLAS detector can sustain a factor of 2.5 in rate which will be achieved by increasing the target thickness. By doubling the running time to 36 days we will achieve the desired statistics and sensitivity.

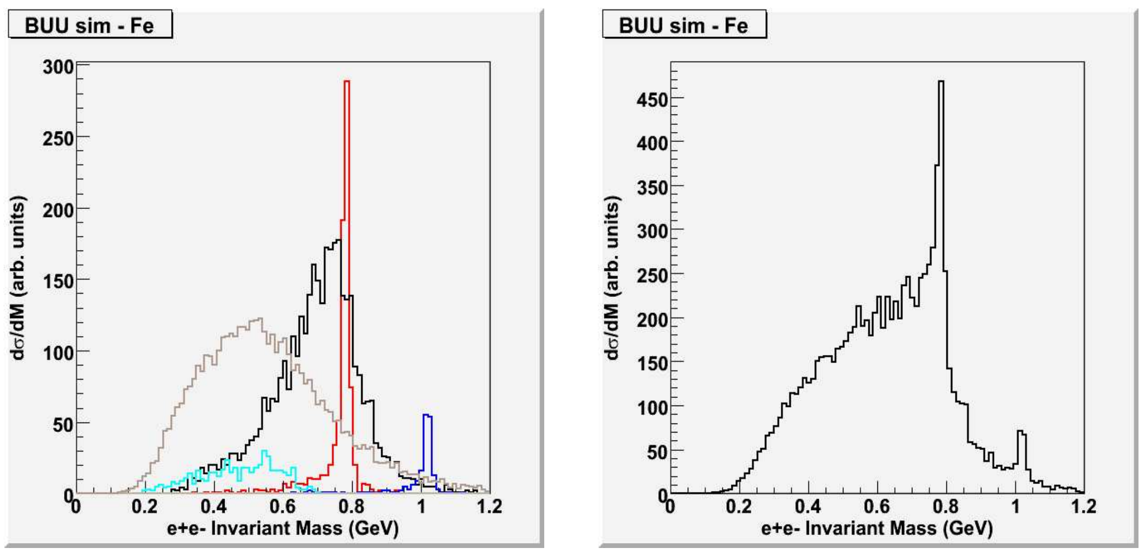

Figure 22: Expected invariant mass spectrum for the new experiment from simulation showing contributions from various channels. The curves are: ω (red), ϕ (dark blue), ω Dalitz (light blue), and ρ (black) channels. The expected uncorrelated background is shown in brown.

6 Manpower

Spokespersons:

- D. P. Weygand (JLab) Physics, simulations, trigger, data reconstruction, data analysis, particle identification, and e/π discrimination.
- C. Djalali (USC) Physics, particle identification, e/π discrimination, data reconstruction, and simulation.
- M. H. Wood (USC-postdoc) Physics, data analysis, trigger, particle identification, e/π discrimination, simulations, and data reconstruction.
- R. Nasseripour (GWU-postdoc) Physics, background, particle identification, data analysis, preparation, and simulations.

Other Physicists:

- R. Gothe (USC) Physics
- D. Tedeschi (USC) Physics
- S. Strauch (USC) Physics
- L. Guo (JLab-postdoc) Physics, trigger, simulations, data analysis, and preparation.

Graduate Students:

- Upcoming Ph.D. student with thesis on g7b experiment will be stationed at JLab and involved (100%) in data analysis, simulation, target, beam, preparation, and data taking.

All of the physicists have experience running experiments with CLAS and normalization of the photon beam and collimation. The listed manpower has been involved in the first g7 experiment and is already familiar with all aspects of GEANT simulation and of calibration and reconstruction of g7 data. The e/π discrimination technique, particle identification and data analysis procedures and corrections are well defined and documented in the g7a analysis-note [47]. There are experts on all phases and aspects of the proposed extended experiment in our group, to be confident that we will be able to successfully run the experiment and complete the data analysis.

7 Summary

In summary, we propose a new experiment with a photon beam up to 3 GeV on a set of nuclear targets (^2H, Fe, Nb, and Sn) using the CLAS detector. The experiment is designed to search for medium modifications of the light vector mesons ρ, ω, and ϕ via their leptonic decay. The result of the analysis of the previous data set has demonstrated the ability to detect the e^+e^- decay of all three vector mesons [1]. This leptonic decay channel is preferred over the hadronic modes to avoid final-state interactions. The proposed experiment will expand the investigation of in-medium properties of the ρ, ω, and ϕ mesons. The in-medium properties will be studied in two separate ways. The ρ meson will be studied for its decay inside the nucleus due to its small life time ($c\tau_\rho = 1.3$ fm). With the ω and ϕ mesons with their long lifetimes ($c\tau_\omega = 23.4$ fm, $c\tau_\phi = 44.4$ fm), the in-medium properties will be accessed through the absorption. In both cases, heavier targets of Nb and Sn will be used, and the momentum dependence mapped out.

The previous data determined a value of 0.02 ± 0.02 for the mass shift parameter, α, in Fe. These results rule out the prediction of Brown and Rho for a 20% mass shift and Hatsuda and Lee for $\alpha = 0.16 \pm 0.06$ in C and Fe targets. The result of the KEK measurement ($\alpha = 0.09 \pm 0.002$) is not consistent with the JLab results. The focus of the new experiment is to investigate the momentum dependence of the medium modifications predicted by theoretical calculations [20] and address the in-medium width of the ω and ϕ mesons. The modification of the fundamental properties of the vector mesons, such as the mass and width, in a dense medium is currently a key component of understanding QCD. The unique characteristics of the g7 experiment, an electromagnetic probe and a final state uncomplicated by strong interactions, provides a definitive and aggressive statement of the ρ, ω, and ϕ meson properties in a variety of nuclei.

8 Acknowledgment

The g7 group would like to thank U. Mosel, P. Muehlich, J. Weil, O. Buss, and A. Afanasev for providing us with theoretical support during this work.

A Sensitivity Determination

The ratio of the ρ mass distributions for Fe to ^{2}H and C to ^{2}H targets is a clean model-independent method to measure a possible shift in the mass of the ρ. The ratios obtained from the previous data are shown on the bottom panel of Fig. 23. A linear fit was performed to approximate the shape of the ratio of the two mass distributions in the region of interest and was used to estimate the sensitivity to a mass shift. In order to illustrate this sensitivity, the ratios are also obtained using the GiBUU model by generating five times more statistics than in the data. The result is shown in the top and middle panels of Fig. 23 for C and Fe targets, with and without including the prediction of Hatsuda and Lee [3] for the mass shift, respectively.

To investigate the sensitivity of the current data to a mass shift, the slope of the linear fit is shown as a function of mass shift parameter, α, in Fig. 24. The solid (Nb) and dashed (Fe) lines are obtained from simulation by shifting the ρ mass distributions of the Fe and Nb targets and fitting the ratio of the shifted to unshifted distributions by a polynomial of order one. The fit to the data (Fig. 23, bottom) shows a slope of less than 8$\pm$8 MeV (consistent with a small to zero mass shift) corresponding to $\alpha = 0.02 \pm 0.02$. This sensitivity can be improved by increasing the statistics and using a Nb target with a larger effective density compared with Fe (see Fig. 1). The expected sensitivity in α with the new measurement is about ± 0.007 ($\Delta\alpha = 0.02$ within 3σ).

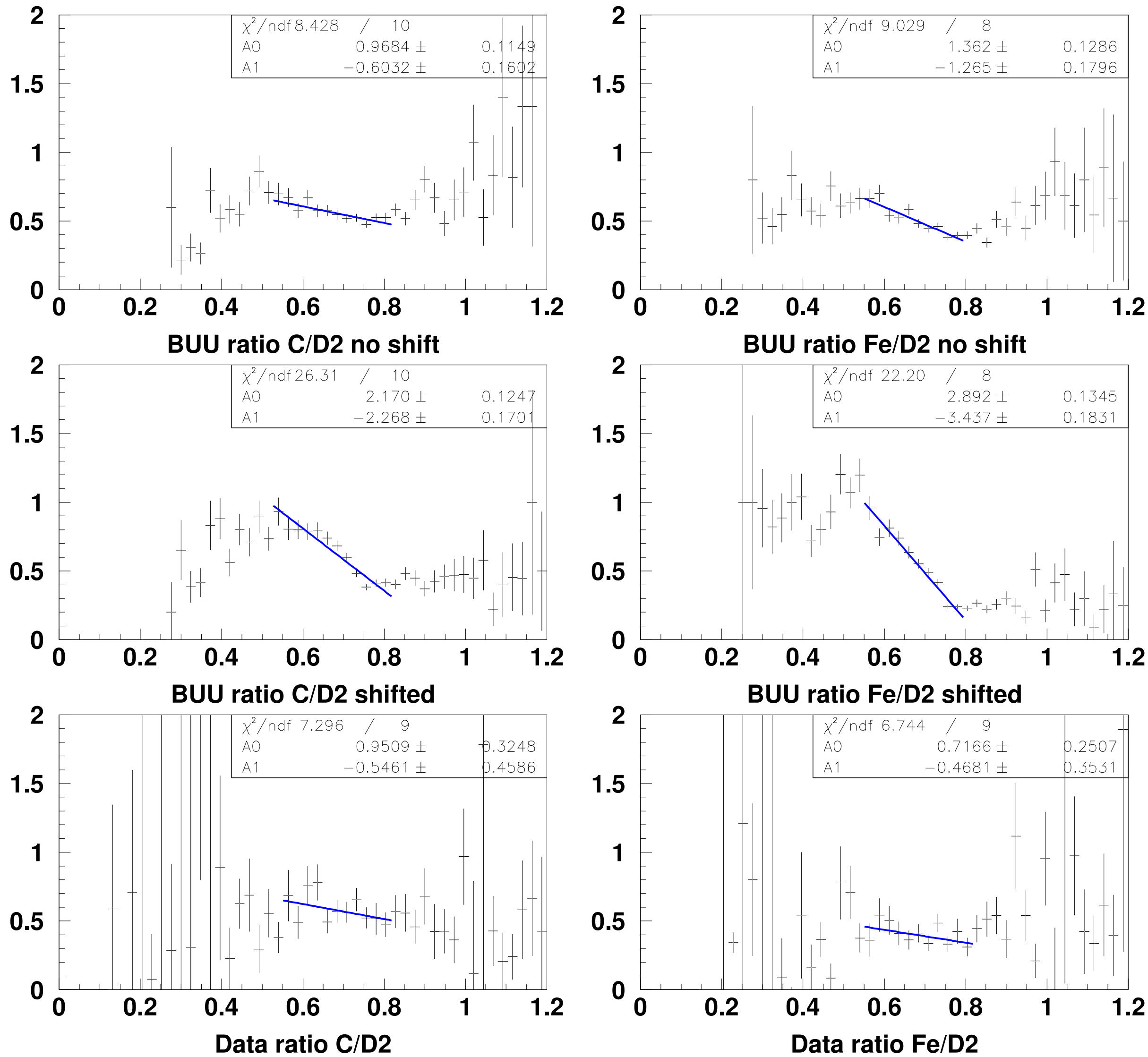

Figure 23: Ratios of the e^+e^- invariant mass for C to ^{2}H (left) and Fe to ^{2}H (right). The ratios are obtained from the g7a data (bottom), and the GiBUU model with (middle) and without (top) the Hatsuda and Lee mass shift. The number of GiBUU events is five times more than the current data. The slope of a simple linear fit shown on each plot is used to investigate the sensitivity of the current data to a mass shift (also see Fig. 24).

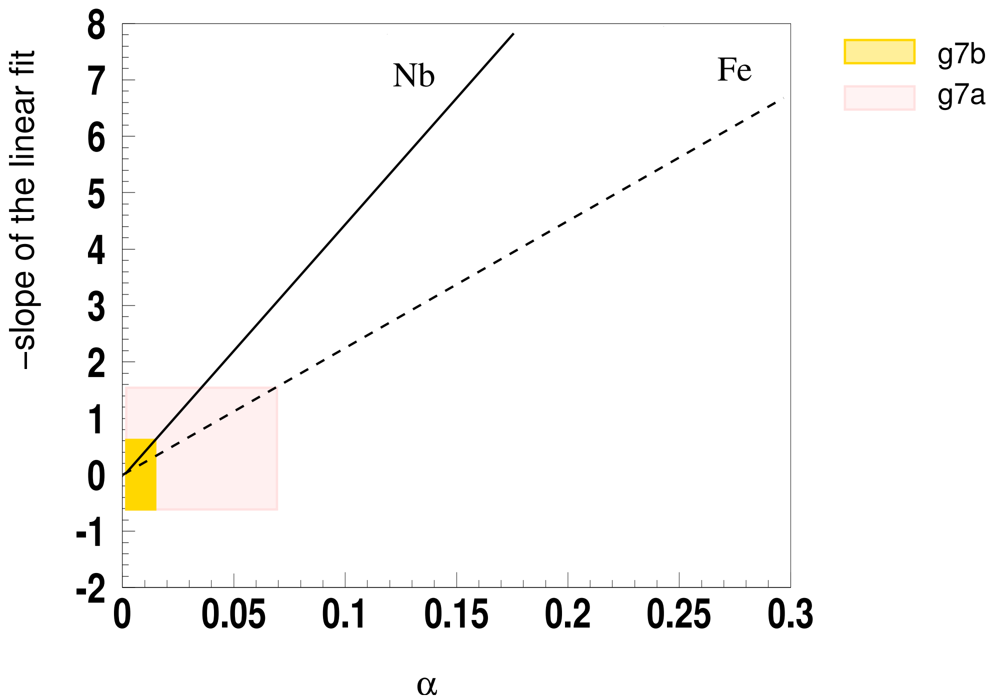

Figure 24: Slope (1/GeV) of the linear fit to the ratio of the ρ mass distributions in the Fe and Nb targets as a function of the mass shift parameter α. The shaded boxes are the g7a (pink) and proposed, g7b (yellow) measurements within 3σ. The Nb target provides better sensitivity compared to Fe.

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